EDL Engineering Constraints

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Overview

- Landing site safety assessment involves evaluation of broad spectrum of risks
  - Uncertainty exists in data set used to evaluate
  - Mars is frequently unkind
  - Risk evaluation involves judgment
  - "Less" risk is always better than "more"

- EDL engineering safety constraints is a discretized set of thresholds
  - Environmental parameters above (beyond?) which additional risk/work exists
  - Discretization process injects error
    - Discretizing a continuum of environmental characteristic into a finite set
    - We only know to be afraid of that which we can conceive of
  - The engineering safety constraints are complex
    - Some of the constraints are very firm and more brittle than others when exceeded
    - Some of the constraints are not as firm
    - Constraints are interconnected

- We offer a brief primer on a subset of the constraints
  - Supports the search for other things to be afraid of
  - Informs science community of environmental characteristic to be considered in the site evaulation
  - General understanding
  - Time constrains discussion

Landing Site Elevation

Constraint

- Requirement: ≤ +1 km MOLA
- Safe haven:
  - ≤ -1 km MOLA
  - ≤ -2 km MOLA most desirable

Possible Trades

- Terrain tolerance
  - Lower elevation sites yield timeline and propellant margin that can be spent on terrain relief tolerance
  - Example: -1 km MOLA site can yield >50 m additional terrain relief tolerance
- Precision
  - Lower elevation sites can sometimes be used to increase precision performance
  - 0.5 km decrease in site elevation may yield ~0.5 km precision improvement
- Robustness
  - Lower elevation sites yield timeline and propellant margin allowing increased system/environment uncertainty

Why We Care

- High elevation sites require the vehicle to be decelerated faster
  - Need enough time to complete EDL events required for safe landing
- More fuel is required to land at high elevation sites
  - Parachute under-utilized (not enough time)
  - Atmospheric density is lower
- Low elevation sites allow the radar to better “see” the eventual landing site

Criticality/Firmness of Constraint

- Cannot exceed +1 km elevation
  - System has extremely limited timeline and propellant margin at +1 km sites
  - Elevation capability increase unlikely
- Elevation directly affects critical resources
  - Altitude/timeline margin
  - Propellant margin
- Timeline/fuel risks are greatly reduced at or below -0.5 km MOLA

Landing Site Terrain

Constraint

- Requirement:
  - ≤ 20° slope for 2 – 10 km length scales
    - Also applies to warning track
  - ≤ 43 m relief at 0.2 – 1.0 km length scales; increasing linearly to 720 m at 2 km length scales
  - ≤ 15° slope for 2 – 5 m length scales

Possible Trades

- Site elevation
  - Reduced site elevation generates propellant and altitude margin that could be used for additional 0.2 – 1.0 km length scale terrain relief (reverse also applies)
  - Example: 1 km lower site yields ~50 m additional terrain relief tolerance
- Precision
  - Lower elevation sites can sometimes be used to increase precision performance
  - Increased precision performance may shrink the area over which the terrain restrictions apply (smaller warning track, smaller landing area)
- Winds
  - Reduced horizontal wind magnitudes and wind uncertainties may shrink the area over which the terrain restrictions apply (smaller warning track, smaller landing area)
- Robustness
  - Reduced terrain relief yields propellant margin allowing increase system/environment uncertainty

Why We Care

- 2 – 10 km length scales: large slopes may spoof the system into beginning powered flight too high or too low
  - Why a warning track: if we land near the edge of the landing ellipse, the radar will be looking at terrain outside the ellipse
- 43 m relief at 0.2 – 1.0 km length scales: a certain amount of propellant and altitude margin is allocated to terrain relief tolerance in powered descent
- 1 km to 2 km length scales: transition smoothly between two length scale restrictions above
- 2 – 5 m length scales: ensures stability and trafficability of the rover in touchdown conditions

Criticality/Firmness of Constraint

- All terrain relief/slope constraints appear tradable, especially at lower altitude sites
- Some statistical element to terrain constraints
  - Where terrain features are located in ellipse (not all locations in ellipse are equally likely)
- Consequence of terrain relief has different criticality depending on direction
  - Down-slopes cause additional propellant usage
  - Up-slopes cause reduced altitude/timeline margin

Day of Landing Winds

Constraints

- Requirement:
  - ≤ 25 m/s horizontal uncertainty between 6.5 – 20 km altitude MOLA
  - ≤ 20 m/s horizontal uncertainty between 3 – 6.5 km altitude MOLA
  - ≤ 20 m/s downward vertical magnitude between 1 – 5 km altitude above ground level

Possible Trades

- Site elevation
  - Lower site elevation yields altitude/timeline margin that can be spent on horizontal wind uncertainty
  - Example: ~300 – 400 m lower landing site elevation can offset ~10 m/s additional horizontal wind uncertainty
- Precision
  - Lower horizontal wind uncertainties increase precision
  - Example: 10 m/s lower horizontal wind uncertainty may reduce landing error ~0.4 – 0.8 km
- Terrain tolerance
  - Lower downward vertical wind magnitudes yield propellant margin that can be spent on terrain relief tolerance
  - Example: 10 m/s lower downward wind can yield ~50 m additional terrain relief tolerance

Why We Care

- 6.5 – 20 km MOLA horizontal wind uncertainty affects altitude and precision performance
  - Spreads parachute deploy Mach "error"
- 3 – 6.5 km AGL horizontal wind uncertainty affects altitude performance
  - Spreads heatshield separation Mach "error"
- 1 – 5 km AGL vertical wind magnitude affects propellant margin
  - Increases powered flight starting velocity and altitude

Criticality/Firmness of Constraints

- Wind constraints are not as firm as other constraints (e.g. site elevation)
- Wind constraints may be exceeded if traded for reduction in other constraints
- Site elevation is most valuable trading chip
  - Impacts altitude/timeline and propellant critical resources

Landing Precision (Miss Distance)

Constraint

- Requirement: ≤ 12.5 km in downtrack direction; ≤ ~10 km in crosstrack direction
- Safe haven: ≤ 16 km in downtrack direction

Possible Trades

- Not really tradable
- Atmosphere
  - Quiescent atmosphere conditions (wind, density structures, etc.) will improve precision performance

Why We Care

- Constraint defines expected landing precision capability of vehicle across range of landing sites
- Terrain safety constraints apply within the potential landing ellipses
  - Exceptions: “warning track” constraint, some atmosphere constraints

Criticality/Firmness of Constraint

- Unlikely to be able to significantly improve performance across landing sites
- Some capability variability with latitude
  - Orientation of ellipse
  - Precision performance
- Some statistical element to precision capability
  - Not all portions of the landing ellipse are equally likely
  - Ellipse more circular than past missions
- Ellipse performance will “never” be known
  - Largely driven by day-of-landing Mars atmospheric conditions

Landing Site Rocks Distribution

Constraint

- Requirement: probability that a rock higher than 0.55 m occurs in a random sampled area of 4 m^2 should be less than 0.5%

Possible Trades

- Not really tradable
- Robustness
  - Reductions in likelihoods of other failure mechanisms may enable a larger failure likelihood allocation for rocks

Why We Care

- Rover mobility system can accommodate rocks up to 0.55 m before the rover lower structure is damaged
- 0.5% of the project allocation for possible failure has been assigned

Criticality/Firmness of Constraint

- Risk of belly pan strike directly impacts probability of safe landing
  - No other constraints can be traded to reduce this impact
  - Vehicle cannot be modified to increase clearance
- Some statistical element to rock constraint
  - Where rocks are located in ellipse (not all locations in ellipse are equally likely)
  - Percentage of chance of failure that can be allocated

Detailed Site Assessment Process

- Site assessment involves detailed environmental characterization and design tuning
  - Monte Carlo performance simulation used as assessment tool

- Environmental characterization process
  - Terrain digital elevation maps required for several purposes
    - Radar/terrain interaction model and assessment of relief/slope tolerance require ~10 m resolution DEMs
    - Touchdown interaction model and rock strike probability assessment likely require high resolution DEMs
    - Data sets: CTX, HiRISE, photoclinometry
  - Computationally intensive detailed atmosphere modeling required to assess altitude and precision capability at each site
    - Mesoscale modeling captures site specific atmosphere features for guided entry
    - LES modeling may be required to capture low altitude features that impact performance

- Design tuning at each site provides most realistic day of landing risk assessment
  - Options exist for modifying the way the vehicle is flown for each site
    - Tuning guided by performance simulation results
    - Exploring design options is time and personnel intensive

- Team has laid groundwork for site assessments for ~5 sites
  - Throughput is largely team constrained
    - Results generation is labor intensive
    - Results synthesis is a small group affair
  - Radar models (utilizing DEMs) in development
  - Atmosphere modeling community engaged
  - Evaluation process has been preliminarily exercised

EDL Constraints Summary

Constraint Summary:

- Landing site elevation is a valuable trading chip
  - System taxed along many dimensions at high altitude sites
  - Margin at and above +1 km elevation sites is very small
  - Winds and terrain tolerance may be purchased with site elevation reductions
- Landing Precision
  - Performance may vary across launch/arrival/latitude/altitude space
  - Sites with uncertain atmospheric conditions (winds and density) degrade performance
- Rocks abundance above 0.55 m directly impacts landing safety
  - Reductions in other constraints do not directly yield additional capability

EDL Safety Assessment Posture:

- Detailed site assessment is needed to understand true integrated risk at any one site
  - Data sets for evaluation are still pending
- Meeting the engineering constraints does not make all sites equal
  - Safety assessment values safer sites more
  - Safety assessment requires relative comparisons of detailed site assessments